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ELECTRICAL SUBSYSTEM FOR A 2- TO 15-KILOWATT BRAYTON POWER CONVERSION SYSTEM

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16. Abstract

A 2- to 15-kW_e Brayton power conversion system is undergoing extensive experimental evaluation at the Space Power Facility of the Lewis Research Center. Life and performance tests on individual subsystems and components are being carried on concurrently. This report provides a brief description of the power conversion system, with details of the electrical subsystem, its components, and some recent design improvements. Performance has been evaluated under design, as well as off-design conditions, in both the transient and steady-state operating modes. Performance characteristics of the electrical components and of the complete electrical subsystem are tabulated for several operating conditions. A summary of operating hours is also included.

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SUMMARY

The electrical subsystem of the 2- to 15-kilowatt-electric Brayton power conversion system includes the engine control system, the electrical control package, the dc power supply, the parasitic load resistor, the inverters, and required instrumentation. This subsystem is undergoing extensive experimental evaluation both on an individual component basis and as part of the complete flight-configured power system. Tests were performed under a variety of conditions including high and low ambient temperatures, vacuum and atmospheric pressures, steady-state and transient operating modes, and design as well as off-design conditions. To date, the Brayton system has accumulated over 2560 hours of operation. Performance confirms earlier theoretical and test data. For vehicle (user) loads in the 0- to 10-kilowatt range, the housekeeping power necessary for engine control and monitoring is approximately constant at 1.0 kilowatt, subject to intermittent additional loads of from 0 to about 0.6 kilowatt during battery charging. Line-to-neutral rms voltage is steady within ±1.5 volts. Frequency depends upon user load and ranges from about 1230 hertz at zero load to 1200 hertz at maximum load.

INTRODUCTION

The NASA Lewis Research Center Brayton cycle technology program, initiated in 1963, has advanced through the design and fabrication stages to the component and system testing phases currently in progress. A description of the system under development was presented by Klann (ref. 1) in 1968. A subsequent paper by Brown (ref. 2) in 1969 reported progress and outlined some of the testing to be carried out at the Space Power Facility. Reference 3 describes the performance of the complete Brayton power conversion system (hereinafter for brevity called the engine) and compares the test results with those predicted analytically in reference 4. A description of the electrical

subsystem and its performance as an integral part of the engine as it then existed was presented in reference 5. In 1971 Klann and Wintucky (ref. 6) reported current status of the engine and discussed recent design improvements.

A number of new concepts and designs have been incorporated into the electrical subsystem as part of the continuing effort to advance the technology and improve the system. Recent modifications include (1) the addition of a motor-start inverter which simplifies engine startup and eliminates the open-loop operation required by the gas injection procedure during startups; (2) the addition of solid-state heater control logic to automatically control the temperature of the gas storage bottle and thus prevent partial liquefaction and/or separation of the helium-xenon gas mixture; (3) the replacement of the low-level signal conditioner power supplies with a new improved design to eliminate interference resulting from high noise level and at the same time reduce power requirements; and (4) the replacement of the silver-cadmium batteries by nickel-cadmium types when the original batteries reached the end of their useful life.

This report briefly describes the complete electrical subsystem and its major components with emphasis on recent changes and improvements and presents engine performance with these improvements.

DESCRIPTION OF THE BRAYTON SYSTEM

The Brayton power system discussed in this report is a self-contained 2- to 15-kilowatt electrical power system suitable for space applications. Figure 1 is a schematic representation showing the major subsystems which compose the power system. The heat source subsystem, which adds heat to an inert working gas, may consist of any energy source that can provide heat at the proper temperature. For space applications two energy sources of interest are radioisotopes and solar mirrors.

The hot gas leaving the heat-source heat exchanger drives the turbine to produce useful work, part of which is absorbed by the compressor, and the remainder of which is converted to electrical energy by the alternator. The turbine, compressor, and alternator make up the Brayton rotating unit (BRU). The recuperator serves the dual function of removing the excess heat from the gas as it leaves the turbine and preheating the gas returning to the heat-source heat exchanger. The heat-rejection subsystem disposes of the waste heat by means of the waste heat exchanger, redundant liquid coolant loops, and a radiator. This subsystem also provides for cooling of the alternator jacket and the four cold plates on which the electronic components are mounted. The gas management subsystem maintains the proper gas inventory in the primary loop and provides the jacking gas required for startup. And finally, the electrical subsystem regulates and controls operation of the power system. This subsystem is discussed in detail in the remainder of this report.

In figure 2, an electrically heated Brayton system is shown in the vacuum chamber of the NASA Space Power Facility. In this configuration, an electric heat source and a facility-cooled heat-rejection system are used to test the basic power conversion system which includes the electrical subsystem.

DESCRIPTION OF THE ELECTRICAL SUBSYSTEM

The electrical subsystem of the Brayton power system is a flight-configured, functional part of the power system. It is engine-mounted, self-powered, and totally integrated with the remaining subsystems which compose the basic power system. Table I is a reference listing of the electrical subsystem components, contractor, and contract number. In summary form, the electrical subsystem performs the following functions:

(1) It controls and regulates alternator output voltage.

(2) It maintains line frequency (1200 Hz) within design tolerances by controlling alternator shaft speed with an electrical parasitic loading technique.

(3) It distributes and provides switching of all electrical power used for housekeeping and supplied to the user bus.

(4) It supplies its own internal source of dc power during periods of engine startup, normal steady-state operation, and shutdown.

(5) It supplies a source of 400-hertz, 45-volt rms three-phase power for heat-rejection-loop pump operation.

(6) It provides signal conditioning for all engine instrumentation.

(7) It provides automatic engine operation with manual overrides for all control functions.

(8) It provides automatic shutdown of the engine in the event of an overspeed.

(9) It contains visual and telemetry-compatible data monitoring capabilities.

Figure 3 is a pictorial representation showing each of the items of hardware which compose the electrical subsystem. Functions (1), (2), and (3) are performed by the electrical control package (ECP). The parasitic load resistor (PLR) in conjunction with the ECP accommodates function (2). The dc power supply and batteries provide function (4). For reliability, two identical liquid coolant loops are provided, each requiring an inverter to provide ac power for the heat-rejection pumps used in function (5). The signal conditioner contains all required circuitry to accommodate functions (6) and (8). Finally, the control and monitoring panel provides for functions (7) and (9). Some of these components and the interconnecting harness can be seen mounted on the engine in figure 2.

Figure 4 is a block diagram of the electrical subsystem showing the interconnection of 120/208-volt, 1200-hertz three-phase power, 28/56-volt dc power, and low-level

instrumentation and control signals. The interconnection of approximately 3000 terminal points is represented in figure 4. Details of each of these components are presented in later sections. However, to assist the reader, a brief discussion describing the interfunctional relation of each unit is presented here.

The signal conditioner has an interface with nearly all other subsystem components. All command signals originating from the control console as well as all instrumentation and monitoring signals, including those controlling the gas management subsystem (GMS), are channeled through the signal conditioner. Temperature, pressure, flow, voltage, current, and frequency are examples of instrumented variables which are converted to standard 0- to 5-volt data in the signal conditioner. All control signals for valves, relays or electronic switches pass through the signal conditioner. The control and monitoring functions of the console are so closely related to the signal conditioner that these two units were designed and fabricated under one contract and are designated the Brayton control system (BCS).

Engine dc power is provided by an electronic dc power supply package (PSP) during normal operation and by two 28-volt batteries during engine startup and shutdown. Excitation of most of the control and logic functions and power for all electrical devices are derived from this dc source. A voltage of ±28 volts is converted into the 400-hertz power used to drive the pump-motor assemblies of the liquid heat-rejection loop by static inverters.

Finally, control, distribution, and regulation of the 1200-hertz, three-phase power of the alternator is accomplished by the ECP, which contains the alternator voltage regulator, distribution contactors, current transformers, and speed control circuits. The PLR dissipates excess power as commanded by the speed control to maintain alternator speed within specified limits.

Each of the electrical components which compose the electrical subsystem has undergone extensive testing both on an individual component basis and as part of a complete subsystem. Table II presents a summary of test hours accumulated and singles out the unit presently on test with the maximum accumulated hours.

COMPONENT CHARACTERISTICS

In this section, each of the components of the electrical subsystem is described. Inasmuch as alternator speed control and voltage regulation and the design and performance of the control system are subjects of separate reports (refs. 7 and 8), these items are not covered in as much detail as the remainder of the subsystem.

Alternator

The alternator is a four-pole, solid-rotor, modified Lundell type, three-phase machine whose line-to-line output is 208 volts. A turbine and compressor are attached at each end of the alternator rotor to form a single-shaft BRU. Gas-lubricated thrust and journal bearings support the BRU shaft, which rotates at 36 000 rpm. Alternator cooling is by conduction to dual liquid passages containing the heat-rejection system coolant, looped around the alternator housing.

Two field windings are provided, a series field whose excitation is proportional to alternator line current and a shunt field excited by the voltage regulator as required to maintain alternator line voltage within specified limits. A more detailed discussion of the alternator is given in references 9 and 10.

Brayton Control System

The BCS provides all control and monitoring functions necessary to operate the engine. It consists of two items, an engine-mounted signal conditioner and a control and monitoring console. The signal conditioner is an electronic unit which has interfaces with all of the engine instrumentation and electrical control devices and the control and monitoring console. The composite photograph of the electrical subsystem, figure 3, shows both parts of the BCS. The signal conditioner accepts all engine instrument and logic signals and converts them to a common 0- to 5-volt dc value. It also acts as the interface for the returning command and control functions originating from the control console. The link between the two elements of the BCS consists of 11 multiconductor cables. This hard wire link contains 186 sensing signals, 46 return commands, 34±28-volt dc power leads, 46 shields, and 57 spare conductors.

Of all the electrical components, the signal conditioner and control and monitoring console contain more circuitry with interfaces with the remainder of the engine than any other item of engine hardware. For reliability, critical engine parameters (those on which control action is dependent), are triply redundant. All circuits associated with conditioning these parameters are triply redundant. To assure continued safe engine operation following any single part failure, agreement of two out of three logic circuits is required to initiate a command that will affect engine operation. The requirements, design, and performance of the BCS are discussed in more detail in reference 8.

Electrical Control Package

The ECP contains the alternator speed control circuit and the alternator voltage regulator (VR). In addition to these prime functions, the package contains a number of contactors, including the vehicle load breaker and current transformers for measuring alternator and parasitic load resistor currents. All of these components and/or functions are schematically represented in figure 5.

The VR supplies current to the series and shunt fields of the alternator as required for the generation of the correct line voltage. It consists of two current supplies, one for each field. The series field current supply consists of a current transformer on each phase of the alternator output and a bridge rectifier circuit. The current transformers are sized to provide a total series field current that is approximately 0.09 times the average alternator line current.

The shunt field section of the voltage regulator senses the peak line voltage and compares it with a reference set point to determine the amount of additional field excitation required to provide the required 120-volt rms line to neutral voltage. The output of the shunt field regulator is a pulse-width modulated voltage which, when applied to the alternator field, results in the required average shunt field current. Phase to neutral voltage regulation at from 0- to 10-kilowatt output is approximately ±1.5 percent at a power factor of 0.85.

The BRU is designed to operate at a constant speed of 36 000 rpm, which results in an alternator frequency of 1200 hertz. Since user load requirements are not necessarily constant and small variations in thermal input power must be accommodated, the engine requires a speed control. The form of control utilized by the Brayton engine is electric parasitic loading, whereby the speed control diverts excess alternator power to a parasitic load resistor. Specifically, the control is composed of three separate 6-kilowatt-electric parasitic load control channels that operate over a predetermined band of frequencies. Speed is controlled to within 2 percent of design by using two of the channels; the third channel was included to serve as a backup should one of the other two fail to operate.

The three channels of the speed control are identical; therefore the following discussion describes only one. A single channel of the speed controller comprises a frequency detector, a preamplifier, an amplifier, and a phase-controlled silicon-controlled rectifier (SCR) output stage. The output of the frequency detector is a dc error signal proportional to the frequency error. Amplification of this signal is provided by a two-stage push-pull magnetic amplifier. Firing of the SCR output stage is controlled by a saturable reactor. When this method is used firing angle is directly proportional to the output of the final stage of amplification, which in turn is proportional to the frequency error. The output of each channel uses phase-controlled SCR's as power switches for

loading the fixed parasitic load resistor. Additional information related to the ECP is provided in reference 7.

Direct-Current Power Supply

The dc power supply is a solid-state, flight-configured unit, whose main function is to supply the dc internal power requirements of the Brayton power system. The prime source of dc power is conversion of alternator ac to dc power by means of transformers and diode rectifiers. There are times when alternator ac power is not available, for example, prior to and during a startup condition and during shutdown. During these periods, dc power is still required and is supplied by a pair of batteries, one for 28 volts and one for -28 volts.

The dc power supply also has as secondary functions the requirements to recharge the batteries, provide all the control functions necessary for its operation, and provide monitoring instrumentation for the dc power system parameters. The power supply is represented in block diagram form in figure 6. Input to the dc power supply is from the three-phase, 1200-hertz, 208/120-volt ac alternator to the primary winding of two three-phase stepdown transformers. One of these transformers has a wye-connected primary and the other a delta-connected primary. The secondary windings of both of these transformers have identical six-phase star connections to supply the battery charger circuits with ±42 volts and the engine dc bus with ±28 volts; thus, the three-phase input voltage is transformed into a 12-phase voltage and then rectified. The result is an output with low ripple voltage which is acceptable for engine operation without filtering.

The remainder of the dc power supply is in two functional halves, each with several duties. One half of the supply is for the positive 28-volt bus and 42-volt positive battery charger, while the other half is for the negative complement of these voltages. The two sections are basically identical, and therefore only the positive section is described in detail. This discussion follows the block diagram of figure 6. The rectifier section of the supply is actually three separate circuits made up of fused diodes. One circuit supplies the rectified 28 volts for the dc buses. Another circuit rectifies 42 volts for the charger circuit. A third circuit rectifies voltage to provide a 24-volt reference signal.

The battery charger circuits utilize the 42-volt dc from the rectifier circuits through a series current regulator to maintain a constant 4-ampere battery charging current. A charger for one battery is made up of two paralleled 4-ampere constant-current sources. Each one is individually controlled on and off by the logic circuitry to provide either a 4-ampere or an 8-ampere charge rate depending on the state of charge of the battery. Charger on-off command conditions are discussed as part of the logic

circuit description.

The position of the power relay determines the source of 28 volts supplied to the bus. During normal operation the 28-volt bus is supplied from the internal transformer-rectifier circuits, which are directly connected to the bus as shown. If the bus voltage reference signal drops below a given preset level, and during startup and shutdown, the relay logic places the batteries on the bus as an additional source of power. The relay is also manually controllable to remove the batteries from the bus during extended periods of shutdown to prevent a needless drain of battery charge.

Figure 7 is a block diagram representation of the logic circuits of the Brayton dc power supply. The control logic associated with the battery charger senses terminal voltage and governs when the chargers turn on and off depending on the battery terminal voltage, which is in part a function of the state of charge. The set points are indicated in the block diagram. There is also a manual control switch to command the chargers full on or full off as required. When the output of the ampere-hour-metering circuit indicates a battery less than 90 percent charged, an additional input is provided to the charger logic circuits to turn the charger full on.

Automatic control of the dc power relay is provided by logic circuitry which senses the dc bus voltage and compares it to a 24-volt set point. If the voltage on either bus drops below 24 volts, the relay closes automatically to connect the batteries and remains closed until commanded open by the manual control, as shown in figure 7.

The two batteries are required to provide positive and negative 28-volt dc power during startup and shutdown and for backup in the event of power supply failure. The originally installed silver-cadmium batteries reached the end of their usefull life in May 1970, shortly before the first series engine tests were scheduled for completion.

These batteries each had a nominal capacity of 85 ampere-hours at a 40-ampere discharge rate and could deliver up to 100 amperes continuously for 1 minute. The 25 cells in each battery were hermetically sealed and enclosed in a stainless-steel case which included a built-in shunt to monitor charge and discharge rates and two thermistors to monitor cell temperature. Wet-stand life of the eight batteries used for Brayton engine and electrical subsystem tests averaged approximately 20 months. The two longest lived batteries showed a wet-stand life of 23 months. Engine tests at the Space Power Facility were completed by replacement of the batteries with facility ±28-volt dc power.

In preparation for the second series of tests, the engine silver-cadmium batteries will be replaced by a pair of nickel-cadmium batteries installed external to the test chamber.

Inverter for Heat-Rejection-Loop Pumps

The inverter is a solid-state, flight-packaged unit designed to operate from a 56-volt dc source as provided by the engine dc power supply. The output is a 400-hertz, three-phase, quasi-square wave voltage with a zero dwell time of 60° and peaks of 120° duration when measured phase to phase. Phase displacement is 120° between phases. The inverter is capable of starting and continuously running the three-phase pump motor at up to 200 percent of the rated 9-ampere pump motor requirement. Commands to turn the inverter on or off are provided by the BCS.

The block diagram of figure 8 illustrates the operation of the inverter package. The 56-volt dc power is connected directly to the input terminals. The current passes through a low-pass filter to provide low-radiofrequency impedance to the system neutral and then passes through an audiofilter having a cutoff of approximately 150 hertz, which reduces inverter-induced noise back to the dc bus. This filter also reduces any ripple or modulation that may be present on the dc bus. The low-level series regulator supplies voltage to the oscillators and the inverter overcurrent-protection circuit. The regulator also includes the circuits to turn the inverter on or off by remote command.

The ripple regulator contains the voltage sensing and comparator, as well as the trigger and amplifier circuits required to regulate the dc voltage to the higher level required by driver stages, normally 40 to 45 volts.

The oscillator section consists of the phase A, B, and C oscillators, which generate the basic 400-hertz frequency for the inverter. The phase A oscillator contains a precision L-C series resonant circuit in which oscillation is started by turnon and sustained by regenerative feedback from the output transformer. This oscillator also contains a frequency sensing winding on the coupling transformer, a second winding with a full wave rectifier to provide a bias voltage for the overcurrent-protection circuit, and a third winding, which in series with a saturable reactor provides synchronization voltage for phase C and B oscillators.

The driver stage contains three identical amplifiers, each of which amplifies the output from its respective input coupling transformer to drive the power amplifier for each phase. The output section consists of three identical power amplifiers whose output is a square wave, each displaced by 240° from the others. The phase A and B output currents pass through the primary of a sensing transformer for the overcurrent-protection circuit before connection to the inverter output terminal, while phase C is directly connected to its output terminal. Phase voltages AB, BC, and CA of the inverter output are the difference of the wave shapes composing each pair of phase voltages and result in the quasi-square wave output with 60° of zero dwell. Figure 8 includes typical wave shapes generated at several points within the inverter.

Motor Start Inverter

Engine startup during the initial series of tests at the Space Power Facility was accomplished by gas injection. The jacking gas valve was opened to "float" the BRU rotor by the application of jacking gas at the bearings. Then the makeup and vent valves were opened to generate a gas flow through the turbine and compressor which would cause the BRU to rotate and accelerate to some value of self-sustaining speed dependent upon the temperature and pressure in the gas loop. At this point, all the valves were closed, and the BRU continued to accelerate to rated speed. During the interval that the valves are open the engine operates "open loop," that is, the vented gas is lost and must be replenished through the makeup valve.

Subsequent experiments verified that the engine could be safely started with an external ac source to "motor" the alternator to self-sustaining speed, at which point input power could be disconnected and the working gas would accelerate the BRU to rated speed. With this method of startup, the engine is always in the closed-loop configuration.

Early motor start feasibility testing was accomplished with a separate three-phase variable-voltage, variable-frequency power source set at 400 hertz. These tests showed that self-sustaining speed can be attained at rms voltages as low as 20 volts when the gas temperature at the turbine inlet is more than 370° C (700° F) and system pressure is 10 newtons per square centimeter (15 psia). Time required to motor the alternator to 400 hertz synchronous speed (12 000 rpm) and to reach rated speed (36 000 rpm) can be markedly reduced as gas inlet temperature is increased. A discussion of these tests with a graphical representation of the results is given in reference 11.

An inverter (ref. 12) has been designed to provide the necessary 400-hertz three-phase power for motor starting. The output rating for this unit is 15 kilovolt-amperes at 200-ampere peak current; the output has a square wave with three phases of 26 volts per phase. It will be installed on the engine frame and will be powered directly from the engine batteries.

DISCUSSION OF TEST RESULTS

The Brayton system shown in figure 2 had accumulated a total of over 2560 hours of operation as of June 30, 1970.

As in the section COMPONENTS CHARACTERISTICS, information presented in other reports is not covered in detail. The intent here is to present an overview of the entire electrical subsystem performance with special emphasis on components not covered in references 7 and 8.

Alternator

Test results of the alternator are discussed in detail in references 7 and 9. Alternator efficiency, as a function of power level, tends to be one to two percentage points lower than originally predicted. It is believed this difference is the result of higher than expected internal losses. Additional data (ref. 9) show that for unity power factor loads, the peak efficiency is 93.6 percent at 9.5 kilowatts. Testing of the alternator was performed to determine its electromagnetic performance limits. These tests, reported in reference 10, indicate the maximum alternator electromagnetic capacity to be in excess of 26 kilowatts at a power factor of unity.

Brayton Control System

The two units (signal conditioner and control/monitoring console) and the interconnecting cabling which compose the BCS were designed and fabricated under one contract. This enabled acceptance testing of the two units operating together. Functional testing at ambient temperature and pressure, nominal power, and maximum and minimum electrical stress levels was accomplished by using a load simulator which supplied all instrument and control device interfaces, which normally are provided by the Brayton engine. Additional testing with the signal conditioner mounted on a standard engine cold plate and installed in a vacuum chamber was performed over a range of cold-plate coolant temperatures. In this manner the adequacy of the electronic packaging design relative to conductive heat removal and basic circuit performance could be evaluated under vacuum conditions. With the signal conditioner at 150×10^{-3} torr functional tests of the BCS were performed at the following two conditions: (1) a cold-plate coolant temperature of 46° C (115° F) and the dc power input to the BCS set at ±32 volts, and (2) a coolant temperature of -54° C (-65° F) and the input power set at ±24 volts dc. All instrument conditioning circuits were checked for accuracy, and manual controls on the console were used to operate the valves and contactors on the load simulator. The manual and automatic Brayton engine control and protective logic, including those for emergency shutdown, were verified.

Minor problems were uncovered which required the addition of some filter capacitors; however, with one exception the delivered system met all specifications. The low-level internal signal conditioner power supplies which convert the engine ±28-volt dc to regulated ±10- and +5-volt power were too noisy and interfered with the proper operation of the low-level circuitry. It was necessary to substitute laboratory-type supplies to complete testing. New power supply boards were designed and were installed in the signal conditioner shortly before this report was completed. Preliminary tests indicate

satisfactory performance, with a reduction in signal conditioner power demand of approximately 120 watts.

The design, operation, and performance of the Brayton control system are described in more detail in reference 8.

Electrical Control Package

The ECP was tested at the NASA Lewis Research Center in conjunction with the alternator. All functions described in the COMPONENT CHARACTERISTICS section, including certain dynamic characteristics, were investigated. The details of this testing are reported in reference 5 and are only summarized in this section.

First the VR and speed control were calibrated, and initial functional checking was accomplished by using a laboratory type, three-phase ac power supply. Following this test, the package was incorporated into a test setup which included the Brayton alternator driven by an air turbine, a variable vehicle load, an engine cold plate, and all of the required control and instrumentation. Both the steady-state and dynamic characteristics of the VR and the speed controller were studied in this test facility. Figure 9 shows the speed control characteristic in terms of alternator frequency plotted against parasitic load power. Illustrated in the figure are each of the speed control ranges; that is, channel A begins conducting at 1198 hertz, channel B at 1210 hertz, and channel C at 1218 hertz. Each channel has a control range of approximately 14 hertz and overlaps another by a small amount. The S-shaped characteristic of each curve is due to the SCR firing angle being linearly proportional to frequency error.

Figure 10 shows the VR shunt field current response to variations in alternator line voltage. Clearly illustrated is the effect of current regulation as the line voltage approaches 120 volts. Additional information relative to the testing of the ECP can be obtained by referring to reference 7.

Direct-Current Power Supply

A number of tests at various test sites are being conducted on the dc power supply. The contractor as part of the design and fabrication contract was required to place one unit on endurance test. This life test began in September 1968 and as of June 18, 1971, had accumulated nearly 17 000 hours of operation with only minor problems.

Of the three additional units fabricated, one is designated as a spare, one is part of a complete electrical subsystem test under vacuum conditions, and the third is supplying dc power for the engine presently under test at the NASA Lewis Research Center

(fig. 2). Prior to being incorporated into a larger system each supply is given a detailed functional inspection and test. The functional test verifies that all circuits described in the COMPONENT CHARACTERISTICS section are fully operational.

Recalling the earlier design discussion which described the origin of the 12-phase ripple (relative to the 1200-Hz fundamental), the resultant output is now examined. The dc output of the supply is shown in figure 11. Summation of the rectified, 12-phase, transformer outputs results in a dc voltage having a 14 400-hertz ripple. Such a design permits the exclusion of filter circuits which reduce conversion efficiency. Plotted in figure 12 is supply conversion efficiency as a function of dc load. The dc supply, when operating as a functional part of the Brayton engine, is required to deliver relatively constant power for all steady-state operating conditions except battery charging. At the nominal operation point the conversion efficiency is seen to be about 88 percent. A more comprehensive account of operating parameters at other than nominal conditions is presented in table III. Shown are the effects of the battery charger loads on supply performance. The lowest overall efficiency, 79.5 percent, results when both battery chargers are operating at a full 8-ampere charge rate.

Inverters

Testing of the inverters has proceeded along similar lines to that for the dc power supply. The contractor is performing a combined inverter-pump motor assembly life test which began on April 4, 1969, and had accumulated nearly 14 000 hours as of June 15, 1971. Two units (normal engine complement due to redundant heat-rejection-loop pumps) are being tested under vacuum conditions as part of a complete electrical subsystem test. An additional two units are on the engine under test at the Space Power Facility. As of June 30, 1970, 2560 hours of actual engine operation using the inverters to drive the heat-rejection-loop pumps (usually only one operating at a time) had been accumulated. Performance has been totally trouble free and within design specifications. Test results indicate that the total inverter power requirements range from 500 to 600 watts depending upon the dc bus line voltage and the flow rate being delivered by the particular pump under excitation. A corresponding variation in conversion efficiency occurs, which ranges from 0.73 to 0.80 for the pump load power factor of about 0.65. At greater loads and unity power factor, the efficiency approaches a value of 0.90.

Table IV compares more detailed characteristics of three inverter tests, all with the engine pump motor used as the load. Two of the tests were run at the vendor's facility and one at the Lewis Research Center. The data associated with the test run at Lewis are more representative of actual engine operating conditions and indicate the input power to be 510 watts with a conversion efficiency of 0.80 at a power factor of 0.67.

Complete Electrical Subsystem

Complete subsystem testing, as opposed to individual component acceptance and performance testing, is being performed at two locations. One setup is totally oriented toward an evaluation and endurance test of the electrical subsystem (as shown in figs. 3 and 4). All engine functions which have interfaces with the electrical subsystem are simulated with external facility equipment. Electrical input (BRU-alternator simulator) is provided by a three-phase, variable-frequency facility power supply. Additional facility instrumentation has been included in the test to allow for cross checking the engine instrumentation and to permit the evaluation of the behavior of each component when operating as part of the total subsystem.

A second complete electrical subsystem is being tested as part of the Brayton engine in the Space Power Facility vacuum chamber of the NASA Lewis Research Center. Because of the complexity of total engine evaluation requirements, specific data dealing with individual electrical component performance are not available in every case. However, sufficient information is recorded to permit an evaluation of overall electrical subsystem behavior under vacuum conditions.

Several data points at various engine operating conditions in vacuum are presented to illustrate electrical subsystem performance at several output power levels. The pertinent data are listed in table V. The first grouping of data give typical values of gas loop parameters. The second group, alternator data, is information which is either measured or calculated directly from engine instrumentation. The next group, vehicle user load, represents the electric power demand of a user. It should be noted that the electrical load profile for a typical mission is seldom constant. The result in Brayton engine performance is the controlled dissipation of more or less power through the parasitic load resistor by the speed control to maintain engine speed within design limits. In order to illustrate this characteristic, data representative of a range of user loads are listed. Within the limitation of instrument accuracies, the resultant value of parasitic load power listed varies in such a manner as to make the sum of vehicle load power, total housekeeping power, and parasitic load power equal to the gross alternator output power. The next group shows engine loads supplied from the ±28-volt dc bus. The values shown for the engine control system are those which existed prior to replacement of the series regulated low-level power supplies in the signal conditioner. More recent tests show that power demand has been reduced by approximately 120 watts as a direct result of replacement of these power supplies by the more efficient switching regulated supplies. Except for periodic battery charging, the dc bus load remains relatively constant regardless of alternator or user power level. The slight imbalance between positive and negative bus totals is due to the large number of signal conditioner circuits which operate positive with respect to ground. The last group, housekeeping power,

represents all electrical power used by the engine to operate the engine. The values listed represent power supplied by the alternator to each of the components for their operation. This includes all losses and conversion efficiency penalties.

From table V it can be concluded that a value of approximately 1000 watts is required for housekeeping and that the remainder minus some minimum PLR residual for contingencies is available to the user.

Three significant modifications to the electrical subsystem have been made in preparation for the second series of tests at the Space Power Facility:

(1) The engine batteries, discussed in the COMPONENT CHARACTERISTICS section, had reached the end of their useful life and are being replaced by a pair of nickel-cadmium batteries.

(2) An inverter for motor starting the engine will be added. This unit is discussed in the section COMPONENT CHARACTERISTICS. Some modifications to the electrical subsystem were required: a three-pole, single-throw, normally open relay was installed in the ECP to isolate the inverter output from the engine power output during normal operation. This relay (see fig. 5) is held closed only during motor start. A second relay, built into the inverter package, also normally open, connects the inverter input to the batteries for motor start. Control of both relays is accomplished from the Brayton control system. And finally, the series field is temporarily shorted for the motor start sequence, and a loading resistor is connected across the shunt field to protect the control system from the high field voltages generated during motor start.

(3) The heater circuit that controls the temperature of the working gas in the GMS bottle was modified to provide more adequate control. At low environmental temperatures it is possible that the helium-xenon mixture may partially liquefy; separation of the gases may result, or the volumetric proportion of the gas mixture may change. Control logic circuits were installed within the ECP to provide automatic operation of the GMS bottle heater (see fig. 5).

CONCLUDING REMARKS

Each of the components which compose the Brayton engine electrical subsystem have been tested as individual packages, as smaller subsystems, and as part of the complete engine system. In some cases individual components were tested both at atmospheric pressure and under vacuum conditions over a range of temperatures. In addition, the integrated electrical subsystem has undergone testing as a complete package in a configuration where all external interfaces were simulated and also as part of a complete Brayton engine. In both of these tests the subsystem was operated in a vacuum environment over a range of cold-plate coolant temperatures.

Table II is a compilation of accumulated test hours of individual components and of total subsystem operation. In all but one case, component performance was satisfactory, and no redesign was required. The one exception was noisy, low-level power supplies internal to the signal conditioner. During the period required for redesign and fabrication of new circuit boards, external supplies were used.

From the results of testing the complete Brayton engine in the NASA Lewis Research Center Space Power Facility, it has been demonstrated that the electrical subsystem fulfills all of its required functions related to control, distribution, regulation, and monitoring of the power conversion system. Startup and shutdown of the engine by the electrical subsystem has also been demonstrated. The total alternator power required to accomplish these functions is a relatively constant housekeeping load of approximately 1000 watts, plus a small parasitic load residual to accommodate slight variations in the system operation point.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 16, 1971,
112-27.

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TABLE I. - SUMMARY OF BRAYTON ELECTRICAL

SUBSYSTEM HARDWARE CONTRACTS

Contract	Description	Contractor
NAS 3-10935	Brayton cycle cooling pumps	Pesco Products Cleveland, Ohio
NAS 3-10935	Brayton cycle inverters	Gulton Industries Inc. E.M. Division, Hawthorne, California[a]
NAS 3-10943	Brayton cycle control system	AiResearch Manufacturing Company Phoenix, Arizona
NAS 3-10936	Brayton cycle dc power supply	Gulton Industries Inc. E.M. Division Hawthorne, California
NAS 3-10977	Brayton cycle parasitic load resistor	Heat Engineering and Supply Company San Gabriel, California
NAS 3-9427	Brayton cycle speed control and voltage regulator	AiResearch Manufacturing Company Phoenix, Arizona
NAS 3-11784	Brayton cycle electrical control package	Hayes International Huntsville, Alabama
NAS 3-11898	Brayton cycle cold plates	AVCO Aerostructures Division Nashville, Tennessee
NAS 3-11257	Brayton cycle contactors	Hartman Electric Manufacturing Company Mansfield, Ohio

[a]Subcontractor to Pesco Products

TABLE II. - BRAYTON ENGINE ELECTRICAL COMPONENT

AND SUBSYSTEM TEST RECORD AS OF JUNE 18, 1971

Component	Number of units tested	Total hours for all units	Maximum hours for single unit
Alternator (BRU)	4	9 306	5 730
Engine control system	2	7 645	4 084
Electrical control package	2	7 671	4 961
DC power supply package	4	24 115	16 449
Inverters	7	23 672	14 327
Electrical subsystem test	1	4 084	4 084
Complete engine	1	2 561	2 561

TABLE III. - BRAYTON POWER SUPPLY

EFFICIENCY FOR ALL COMBINATIONS

OF CHARGING RATES

Operating parameter	Charging rate				
	0	1/4	1/2	3/4	Full
	Power, W				
Three-phase ac input	1402	1661	1869	2110	2374
dc bus output	1244	1244	1244	1244	1244
Charge output	0	160	320	480	640
Total output	1244	1404	1564	1724	1884
Efficiency, (output/ input)×100, percent	88.9	84.5	83.6	81.7	79.5

TABLE IV. - COMPARISON OF INVERTER OPERATING CHARACTERISTICS AT

VARIOUS VOLTAGE AND PUMP OPERATING CONDITIONS

Unit tested	Input			Flow rate		Output					
	dc voltage, V	Current, A	Power, W	g/sec	lb/sec	V/phase	A/phase	VA total	Total power, W	Power factor	Efficiency, percent
Unit for SPF (at vendor)	58.3	10.4	605	204	0.45	46.2	8.90	713	457	0.64	76
Life test (at vendor)	59.2	10.2	602	204	.45	46.8	8.85	715	446	.63	73
Unit for CW-19 (at Lewis)	55.0	9.25	510	177	.39	44.1	8.00	610	406	.67	80

TABLE V. - TYPICAL ELECTRICAL SUBSYSTEM PERFORMANCE FOR A RANGE OF ENGINE AND USER POWER LEVELS

[Testing at Space Power Facility under vacuum conditions.]

Run	Engine parameters								Alternator data					
	Turbine inlet temperature		Compressor inlet temperature		Compressor outlet pressure		Average electronic cold-plate temperature		rms average line to neutral phase voltage, V	rms average line current per phase, A	rms total V-A	Power output, W	Frequency, Hz	Power factor, percent
	°C	°F	°C	°F	N/cm²	psia	°C	°F						
2862	875	1607	27	81	30.9	44.2	35	94	118.2	34.8	12 320	11 980	1208	97.0
3742	876	1609	27	81	24.6	35.1	37	98	118.0	27.4	9 700	9 340	1231	96.4
4053	873	1603	28	83	24.6	35.1	36	96	119.1	25.6	9 150	9 050	1200	99.0
4102	875	1606	28	83	24.5	35.0	37	98	118.8	26.4	9 400	9 140	1210	97.0

Run	Vehicle user load					Total parasitic load power, W	Engine ±28-V dc bus load					Housekeeping power				
	rms average line to neutral phase voltage, V	rms average line current per phase, A	rms total V-A	Power output, W	Power factor, percent		Total inverter input, W (b)	Total engine control system load, W (c)	Battery chargers, W	Total		dc power supply (assuming 86-percent efficiency), W	ECP speed control, W (b)	ECP voltage regulator power, W (b)	Total predicted power, W (d)	Calculated housekeeping power, W (d)
										+28-V bus, W	-28-V bus, W					
2862	118.2	27.0	9600	[a]9287	96.5	1562	510	352	0	574	288	1000	80	51	1131	1131
3742	0	0	0	0	-----	8190	510	346	0	561	295	998	154	51	1203	1150
4053	119.0	21.8	7800	7868	100	58	510	336	0	584	262	984	63	51	1098	1124
4102	118.9	19.4	6910	6936	100	1081	510	315	0	559	266	960	76	51	1087	1123

[a]Instrument error required back calculation of this data point.
[b]Predicted values based on separate component testing.
[c]Values listed have been reduced to about 220 W with replacement of low-level power supplies in signal conditioner.
[d]Replacement of low-level power supplies in signal conditioner has reduced these values by approximately 120 W.

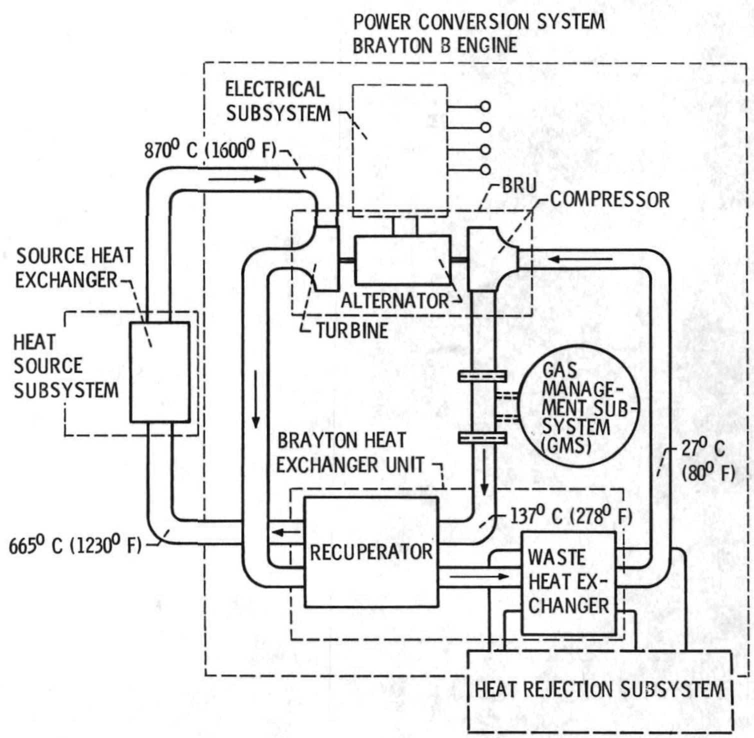

Figure 1. - Schematic diagram of Brayton power system.

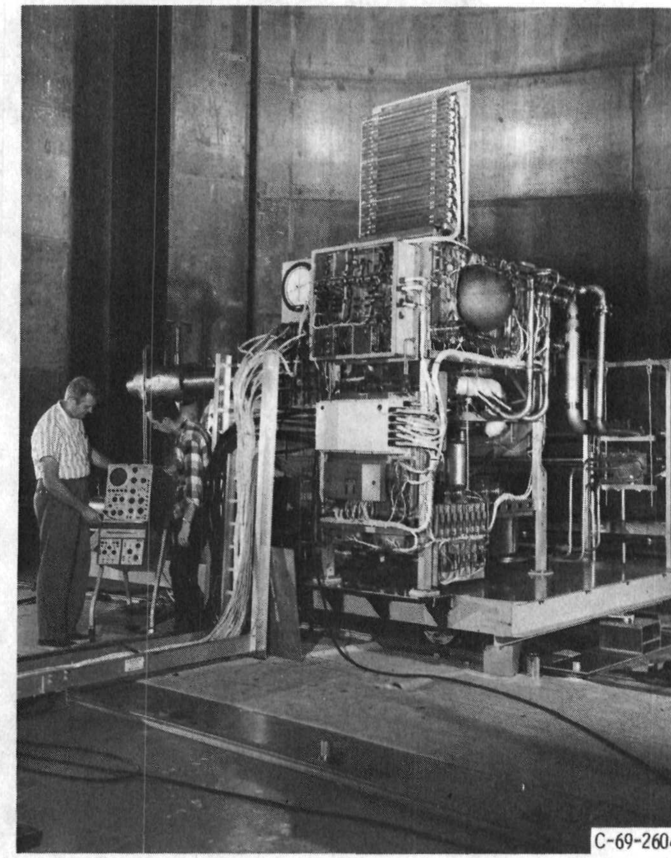

Figure 2. - Brayton power system test engine in Lewis Space Power Facility.

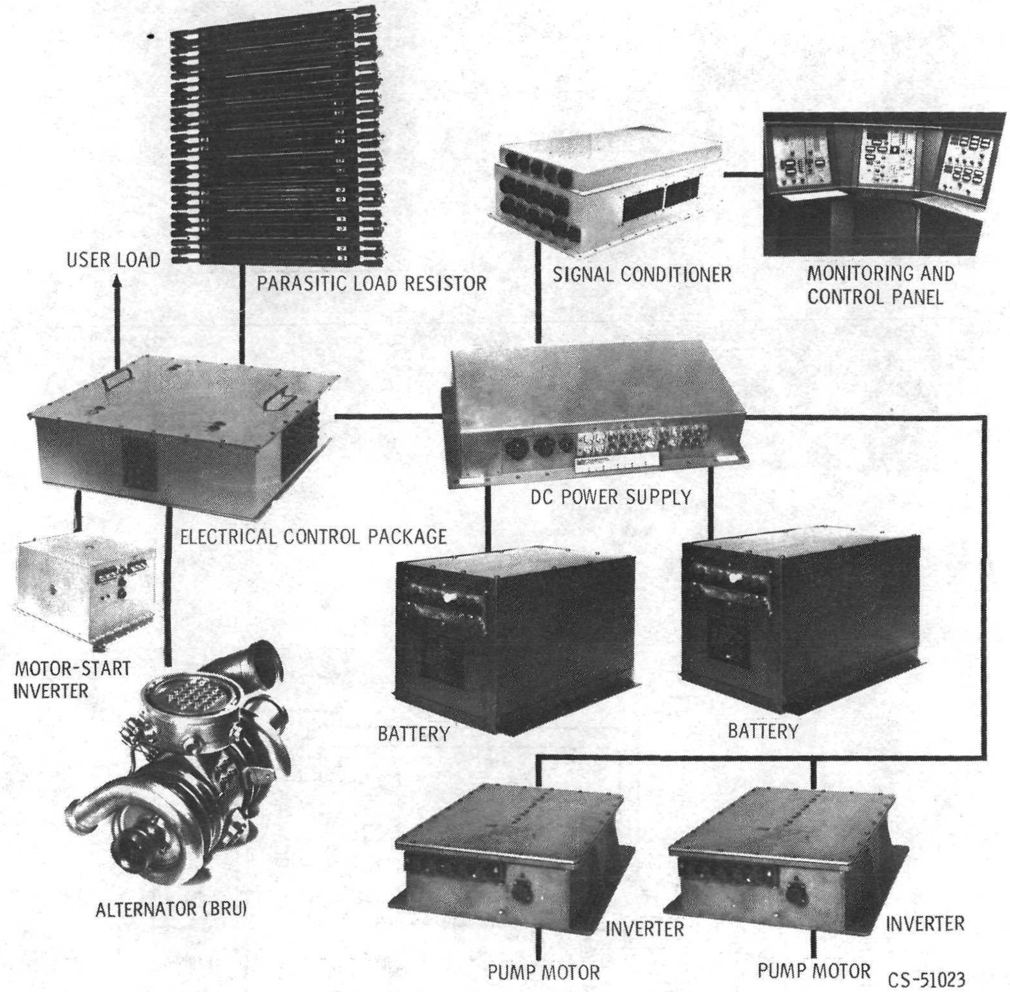

Figure 3. - Brayton electrical subsystem components.

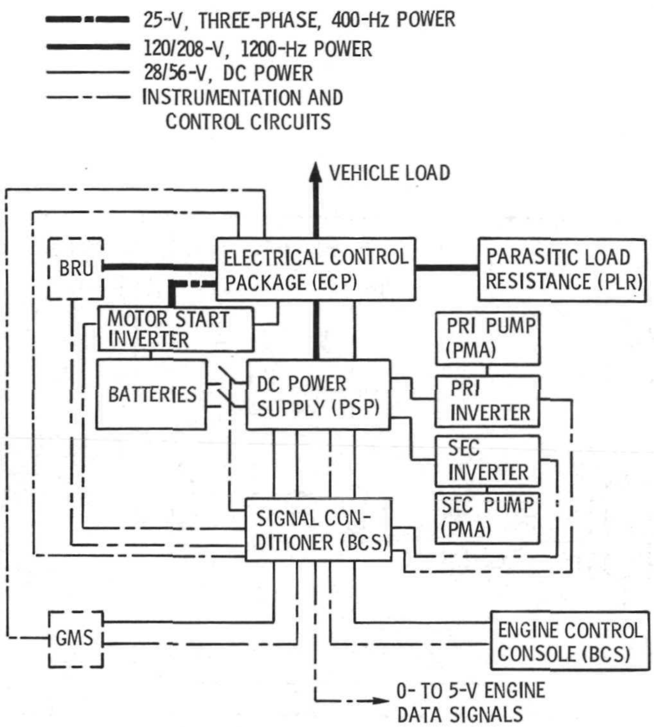

Figure 4. - Block diagram of Brayton electrical subsystem.

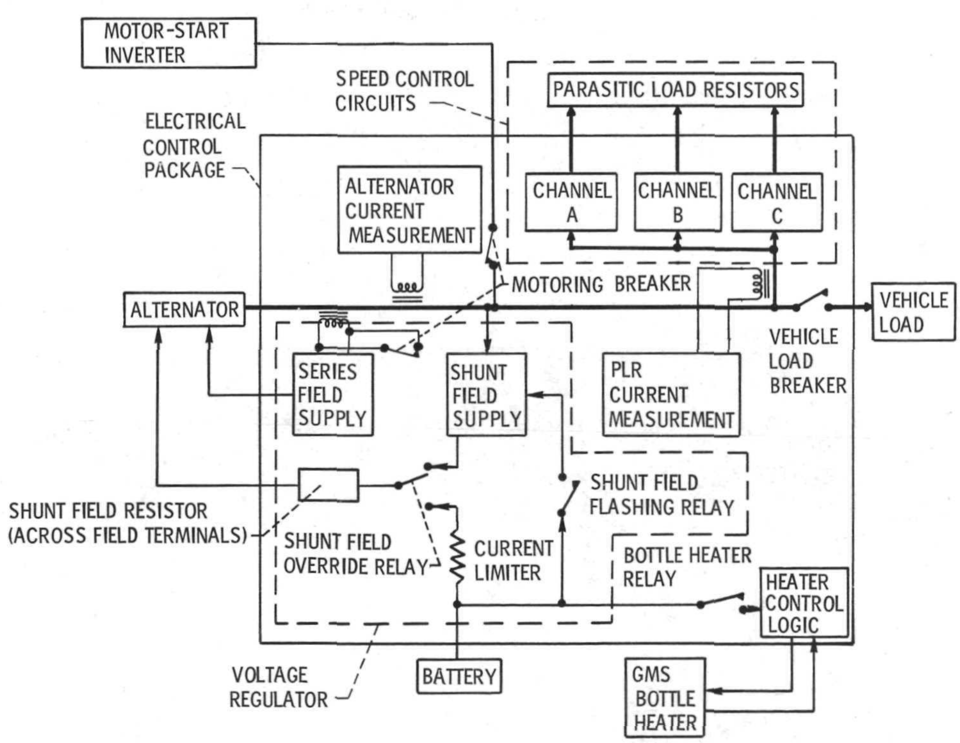

Figure 5. - Block diagram of electrical control package.

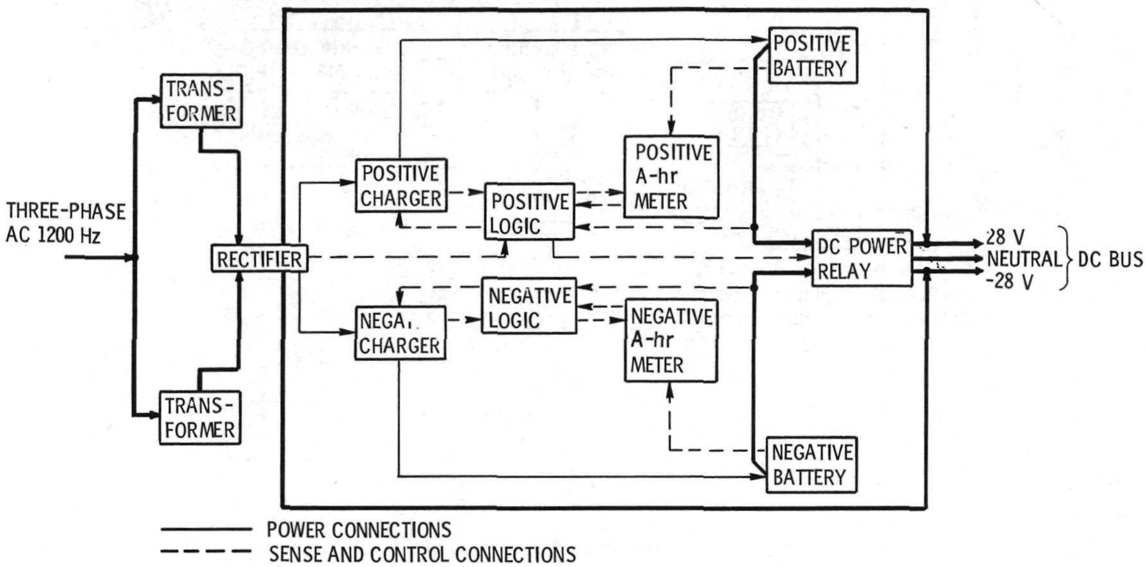

Figure 6. - Block diagram of dc power supply.

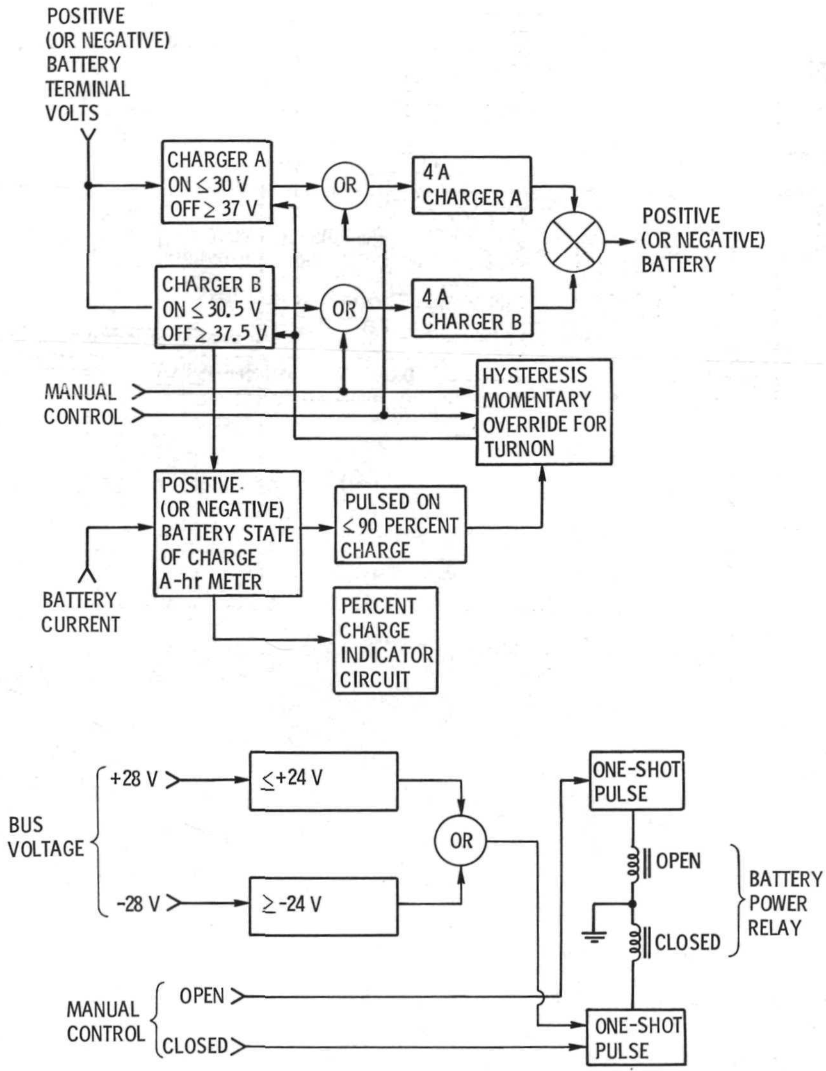

Figure 7. - Logic diagram for Brayton dc power supply. Charger turnon and turnoff voltages are for silver-cadmium batteries.

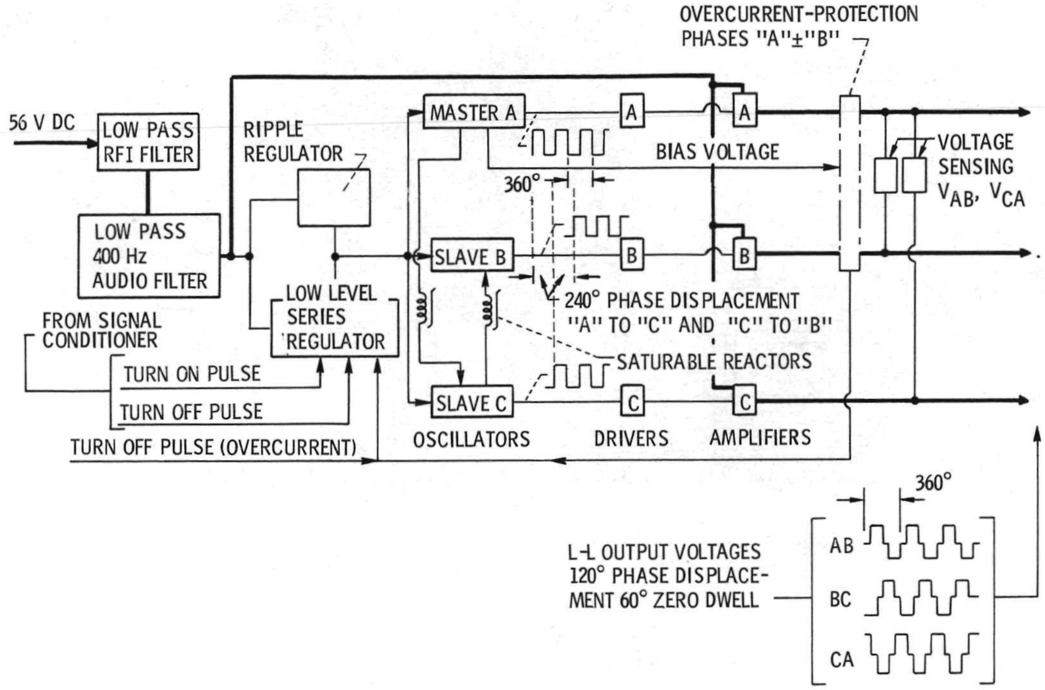

Figure 8. - Inverter-block diagram.

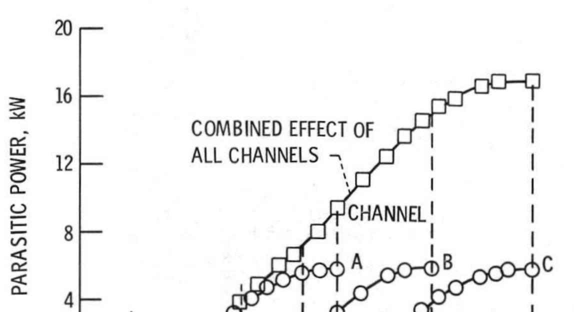

Figure 9. - Calibration curves for the Brayton system speed controller.

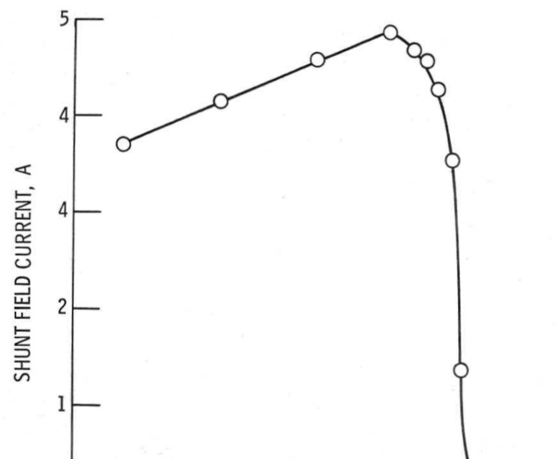

Figure 10. - Voltage regulator characteristics: shunt field current as function of phase A voltage.

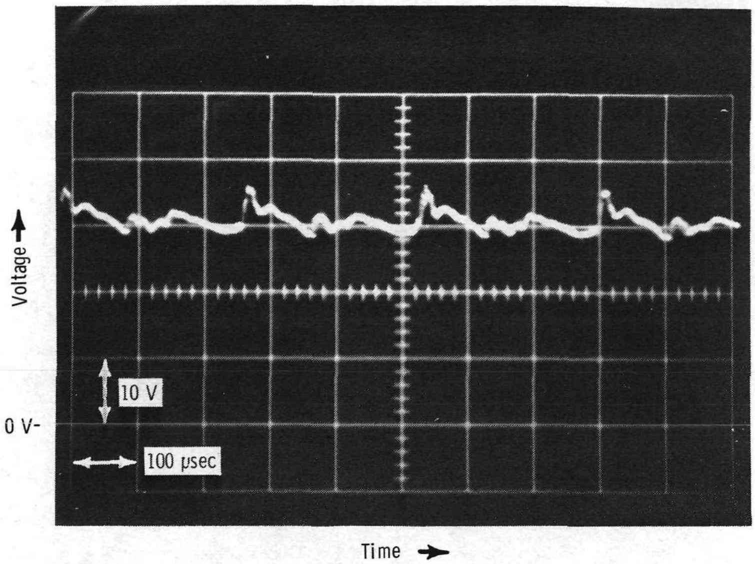

Figure 11. - Photograph of 28-volt dc output of Brayton dc power supply at 5-ampere load. Ripple voltage, 28 volts; bus to common.

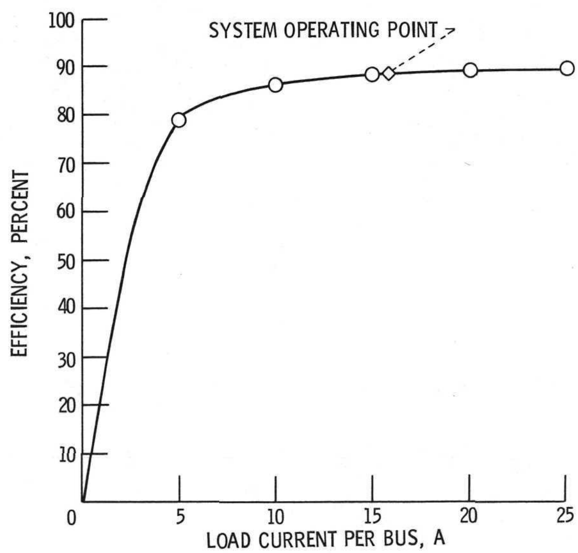

Figure 12. - Brayton dc power supply efficiency as function of load characteristics.

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